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Energy Coherence and Charge Diffusion in Dissipative Reaction

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In the framework of the transport theory, the distribution of coherent energy width versus N/Z in the $^{19}F + ^{51}V$ dissipative reaction is extensively discussed. It can be concluded that the charge equilibrium is reached in the present colliding system. The charge diffusion coefficient is extracted from the theoretical analysis. The linear relation between the distribution width and the average interaction time is ascribed to the charge diffusion process. The effects of the cross correlation between different isotopes on the fluctuation amplitude is also discussed in the paper.

Key words: coherence energy width, distribution width, diffusion coefficient, fluctuation amplitude.

1. INTRODUCTION

Since the fluctuation of the excitation functions of the nuclear reaction was theoretically predicted in 1996 by T. Ericson [1], many research works were devoted to the phenomena. In recent years, several groups started to investigate excitation functions in the dissipative process [2–6]. Some preliminary results show that the fluctuation is due to the correlation between the overlapped intermediate levels of the dinuclear system. This fluctuation is different from the isolated resonance or the Ericson fluctuation in the compound nucleus formation process. It is a unique phenomenon in the dissipative reaction. The cross section fluctuations that commonly existed in the light colliding system where $A_1 + A_2 \leq 100$ and the incidental energy is about 2 times of the Coulomb barrier. The main experimental evidences of fluctuations in the heavy ion-induced dissipative reaction are summarized in the following:

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(1) The excitation functions of the differential cross section present evident fluctuations; this implies the existence of strong correlations among final states.

(2) The coherent energy width varies with the charge number Z and the emission angle of the projectile. The first dependence comes from the fact that the more nucleons transferred, the longer the time required; the second dependence is because the larger the emission angle, the greater the length of time the dinuclear system rotates.

(3) The energy correlation functions are no longer typically of the Lorentz type and there exists the periodical structure due to the interplay between the wave functions of different revolutions.

(4) The angular distribution is asymmetrical due to the quantum coherence of the incident wave packets.

In the previous measurements, only the charge number of projectiles was identified, and the time evolution with the charge number of projectiles was investigated. The cross section fluctuation of a certain element is an overall contribution of its isotopes due to the outgoing channel-channel correlation. It is of great interest to obtain the information about the time-space evolution of the reaction system in the experiment by identifying the mass number A and the Charge number Z simultaneously, studying cross section fluctuations in the A and N/Z (N is neutron number of nuclei) degrees of freedoms, respectively, and discussing the effects of correlations among isotopes.

In the $^{19}F + {}^{51}V$ experiment, the $(\Delta E - E)$ plus time of flight (TOF) technique is adopted, A and Z are simultaneously identified, and dissipative reaction excitation functions are constructed. This enables us to study the effects of correlations among isotopes on the cross section fluctuation and to observe the fluctuations in the excitation functions of the products in the dissipative reaction for the first time.

2. THEORETICAL ANALYSIS OF VARIOUS COHERENT ENERGY WIDTHS OF ISOTOPES IN $^{19}F + {}^{51}V$

The excitation functions of the C, N, O, and F isotopes present obvious fluctuations which are far beyond the statistical errors. The cross-correlation calculation indicates strong correlations among the excitation functions of various isotopes. Using the energy auto-correlation functions (EAFs) and the spectrum density methods (SDM) [8], the energy auto-correlation functions show Lorentz shapes, and the outgoing fragments in the dinuclear system obey the exponential law $e^{-\Gamma t/\hbar}$.

In Table 1 we list the values of Γ_{auto} and Γ_{SDM} as well as corresponding reaction times. The coherence energy widths show pronounced dependence on outgoing channels.

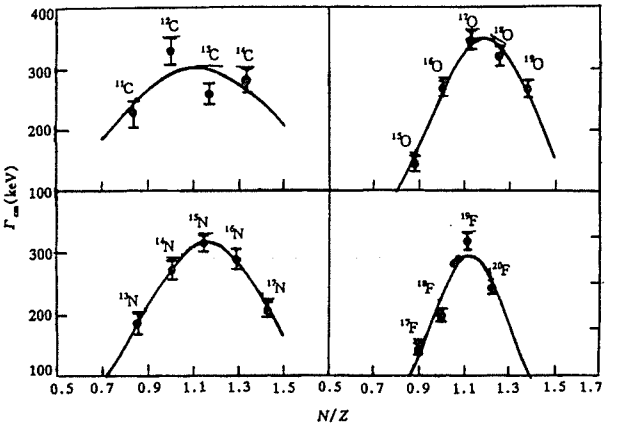

Fig. 1

The relation between the coherent energy width and the ratio of the neutron number to the proton number. The solid line represents the Gaussian fit.

Table 1
Coherent energy widths for different isotopes.

Isotopes	Γ_{auto}(keV)	Γ_{SDM}(keV)	$\tau=\hbar/\Gamma_{SDM}$ ($\times 10^{-21}$s)	Isotopes	Γ_{auto}(keV)	Γ_{SDM}(keV)	$\tau=\hbar/\Gamma_{SDM}$ ($\times 10^{-21}$s)
^{11}C	214 ± 42	225 ± 20	2.92	^{15}O	147 ± 29	145 ± 12	4.53
^{12}C	287 ± 57	330 ± 21	2.00	^{16}O	262 ± 52	268 ± 13	2.46
^{13}C	219 ± 43	259 ± 17	2.54	^{17}O	275 ± 55	346 ± 15	1.90
^{14}C	296 ± 59	281 ± 20	2.34	^{18}O	270 ± 54	320 ± 14	2.06
^{13}N	195 ± 39	185 ± 17	3.56	^{19}O	205 ± 41	269 ± 14	2.45
^{14}N	264 ± 53	272 ± 15	2.42	^{17}F	195 ± 38	160 ± 11	4.12
^{15}N	294 ± 60	315 ± 13	2.09	^{18}F	327 ± 65	230 ± 15	2.86
^{16}N	228 ± 45	291 ± 15	2.26	^{19}F	349 ± 70	388 ± 17	1.70
^{17}N	197 ± 43	208 ± 11	3.16	^{20}F	221 ± 45	291 ± 15	2.26

Table 2
Gaussian fitted parameters for curves in Fig. 1.

$f(x)\bar{\Gamma}\left[\frac{(x-\bar{x})^2}{2\sigma^2}\right]$	$\bar{\Gamma}$	$\bar{x}$	σ
C	300 ± 15	1.13 ± 0.06	0.44 ± 0.14
N	317 ± 10	1.16 ± 0.01	0.29 ± 0.02
O	349 ± 11	1.18 ± 0.01	0.24 ± 0.01
P	358 ± 14	1.13 ± 0.01	0.18 ± 0.01

In order to investigate the variation of Γ with isotopes, the relations between Γ and N/Z are constructed as shown in Fig. 1. The variation of Γ with respect to N/Z is different from those with respect to the charge number Z and to the mass number A. In the latter two cases, Γ reaches the maximum value when the A and Z values of products approach the A and Z values of the projectile, respectively, and decreases when the difference of the A and Z values between the projectile and products increases. The distributions of Γ take Gaussian forms within error bars, except those of the isotopes of C. The discrepancy for element C may be aroused by the structure effect.

In the dissipative reaction, the equilibrium of the A/Z value is a fast process. In the early stage of the formation of the dinuclear system, the equilibrium value of N/Z can be reached. The parameters of Gaussian fits for the isotopes of C, N, O, and F are listed in Table 2. The most probable N/Z value is located between $(N/Z)_P = 1.11$ for the projectile and $(N/Z)_T = 1.22$ for the target, which is much closer to the value of the compound system $(N/Z)_c = 1.19$ within error bars, especially for the isotopes of N and O. For the isotopes of F, the most probable N/Z value is around the value of the projectile 1.11 due to the contribution of the direct reaction. For the isotopes of C, the structure effect is stronger, and the distribution peaks around the value of ^{12}C so that the most probable N/Z value deviates from the expected equilibrium value of N/Z. In general, the mean values of Γ tend to move toward the value of the equilibrium compound system $(N/Z)_c$ and remain almost unchanged within error bars. This means that the equilibrium of N/Z has been reached, though even many degrees of freedom are far away from the equilibrium in the early stage of the dissipative reaction when the reaction products are measured in the vicinity of the grazing angle. This is consistent with the fact of the fast charge equilibrium.

The width Γ increases with the decrease of the charge number of isotopes Z. The longer the reaction time, the more nucleons transfer and the wider the width is distributed. Figure 2 depicts the distribution curves with respect to the charge number of the projectile. The linear relation in Fig. 2 reflects the existence of the diffusion process.

In the transport theory [9], the Fokker-Planck equation for the probability $P(x)$ can be written as

$$\frac{\partial}{\partial t}P(x,t) = -\frac{\partial}{\partial x}[v(x,t)P(x,t)] + \frac{\partial^2}{\partial x^2}[D(x,t)P(x,t)], \tag{1}$$

here $v(x, t)$ is the drift velocity which follows

$$v(x,t) = 2\mu_2(x,t)\frac{\partial}{\partial x}\rho(x,t) + \rho(x,t)\frac{\partial}{\partial x}\mu_2(x,t), \tag{2}$$

and $D(x, t)$ is the diffusion coefficient which obeys

$$D(x,t) = \mu_2(x,t)\rho(x,t), \tag{3}$$

where

$$\mu_2(x,t) = \frac{1}{2}\int_{-\infty}^{\infty}\lambda(x,x',t)(x'-x)^2\mathrm{d}x', \tag{4}$$

with $\lambda(x, x', t)$ being the transition probability from state x' to x per unit time, and $\rho(x, t)$ being the weight of $P(x, t)$. If the drift velocity v and the diffusion coefficient D are constant, respectively, the solution of Eq. (1) is

$$P(x,t) = \frac{1}{\sqrt{4\pi Dt}}\exp\left[-\frac{(x-x_0-vt)^2}{4Dt}\right], \tag{5}$$

and the mean value $\langle x\rangle$ and the deviation can be written as

$$\begin{aligned}\langle x\rangle &= \int_{-\infty}^{\infty}xP(x,t)\mathrm{d}x = x_0 + vt,\\ \sigma_x^2 &= \langle(x-\langle x\rangle)^2\rangle = \int_{-\infty}^{\infty}(x-x_0-vt)^2P(x,t)\mathrm{d}x = 2Dt,\end{aligned} \tag{6}$$

Equation (6) indicates that the drift velocity of the mean value is v, and the distribution width increases linearly with respect to time and is proportional to the diffusion coefficient D.

The Γ's of different elements are in Gaussian distribution. The mean value has very small deviation, so that the drift velocity can be considered zero. The large distribution width means that the diffusion process is clearly existed. In Fig. 3 we plot the distribution width $2\sigma^2$ with respect to the mean reaction time τ, where τ is obtained through the uncertainty relation $\tau = \hbar/\Gamma$ using the $\bar{\Gamma}$ value in Table 2. The distribution width is proportional to the reaction time. According to Eq. (6), the slope of the straight line is the diffusion coefficient which equals to $(0.81 \pm 0.34) \times 10^{21}\mathrm{s}^{-1}$. Due to the effect of the diffusion process, the distribution width increases drastically with respect to the decreases of Z as shown in Fig. 1, which is in accordance with the expectations of Eqs. (5) and (6).

3. STUDY OF THE COHERENT CORRELATION BETWEEN THE FLUCTUATION AMPLITUDE OF THE CROSS SECTION AND THE OUTGOING CHANNELS

In the statistical model, the standard deviation is used to describe the amplitude of the discrepancy

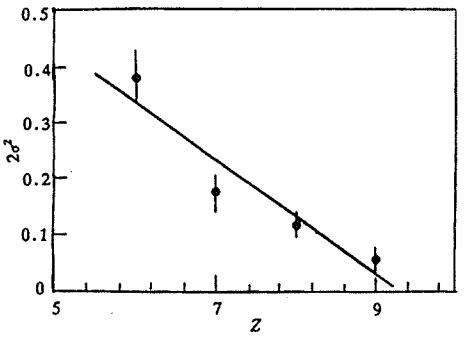

Fig. 2
The relation between the distribution and the charge number of projectiles.

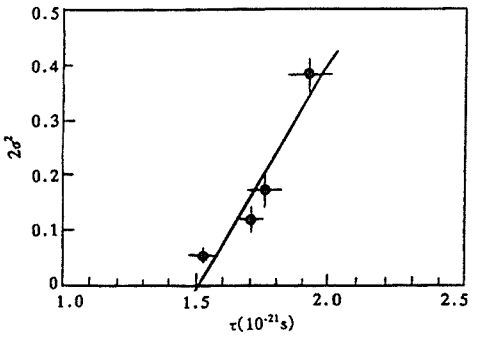

Fig. 3
Reaction time dependent Γ. The solid lines are the linearly fitted results.

from the mean value. In order to measure the fluctuation of the excitation function, the standard deviation is defined as

$$C(0,\theta) = \frac{\langle \sigma(E,\theta)\sigma(E,\theta)\rangle - \langle \sigma(E,\theta)\rangle^2}{\langle \sigma(E,\theta)\rangle^2} \quad , \tag{7}$$

where $\langle \sigma(E, \theta)\rangle$ is the averaged cross section, and $\langle\rangle$ implies the arithmetic average over the measured energy range.

In D.M. Brink's theory, the amplitude of the standard deviation is inversely proportional to the number of final states N_{eff}, i.e., $C(\varepsilon = 0, \theta) = 1/N_{\text{eff}}$. It is impossible to distinguish micro channels of different final states in the measurement due to the continuous distribution of the energy spectrum. Thus the measured cross section contains the contribution from many final states. There are many quantities which can be used to identify micro outgoing channels, e.g., the energy, mass, charge, spin and parity. In the experiment one mainly uses the mass number, charge number and the energy of the projectile to identify reaction channels in the dissipative reaction. The cross sections obtained using different identification methods involve different numbers of micro outgoing channels, so that the values of the standard deviations are also changed. The de-excitation of the excited primary products through the emissions of the γ-rays and neutrons as well as light particles makes the identification of the outgoing channels even more complicated.

In the reaction $^{19}F + {}^{51}V$, the cross sections for the element C, N, O, and F are the sum of the cross sections from corresponding isotopes. The number of effective micro outgoing channels for each element should be greater than that for its corresponding isotope. In other words, the reaction channels identified by the charge number contain the channels with different A, which means that the identification would be more accurate if one uses both A and Z.

Specifically, $C(0, \theta)$ for the element F should be larger than that for the isotopes ^{17}F, ^{18}F, ^{19}F, and ^{20}F, as shown in Table 3. The deviations for the elements C, N, O, and F are nearly the same as that for the isotope which has the highest yields and is far away from the theoretical predictions. For example, the deviation for the element F reaches 0.179 ± 0.039. The inverse of the deviation for each element should be the sum of those for isotopes $^{17\text{-}20}F$, and the calculated deviation is 0.043 ± 0.010. This value obviously differs from the experimental one. Therefore, the correlation among outgoing final states makes the amplitude of cross section fluctuation much more different from the prediction. Because of the correlation, the discrepancy between the fluctuation amplitude for the element and sum

Table 3
Standard deviations of different elements and isotopes.

Element isotopes	Normal variation	Element isotopes	Normal variation	Element isotopes	Normal variation	Element isotopes	Normal variation
C	0.096 ± 0.013	O	0.087 ± 0.014	N	0.093 ± 0.012	F	0.179 ± 0.039
^{11}C	0.187 ± 0.037	^{15}O	0.310 ± 0.092	^{13}N	0.120 ± 0.017	^{17}F	0.236 ± 0.075
^{12}C	0.098 ± 0.011	^{16}O	0.091 ± 0.013	^{14}N	0.090 ± 0.013	^{18}F	0.125 ± 0.029
^{13}C	0.099 ± 0.014	^{17}O	0.094 ± 0.014	^{15}N	0.095 ± 0.012	^{19}F	0.297 ± 0.064
^{14}C	0.132 ± 0.017	^{18}O	0.089 ± 0.17	^{16}N	0.126 ± 0.021	^{20}F	0.137 ± 0.028
		^{19}O	0.306 ± 0.054	^{17}N	0.214 ± 0.032		

of the fluctuation amplitudes for its isotopes becomes pronounced. Furthermore, the number of micro outgoing channels, in fact, reaches tens to several tens, but not the expected hundreds.

In this paper, the variation of Γ with respect to the *N/Z* value of projectile is presented, the experimental evidence of the Gaussian distribution of Γ with respect to *N/Z* is observed, and the distribution width with respect to the charge number of outgoing channels is also shown. The Gaussian distribution features are discussed in the framework of the transport theory. From the value of the most probable *N/Z*, it can be concluded that the charge equilibrium is reached. The dependence of the distribution width on the charge number of outgoing channels is interpreted by referring to the diffusion process. The dependence of the cross section fluctuation amplitude on the correlation among final channels is discussed in detail. It is shown that the correlations among final states make the excitation function fluctuation in the dissipative process even more pronounced.

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